Final Report
Earthquake Hazards Program Assistance Awards

USGS Award Number: G16AP00105

Multi scale/signal imaging of the San Andreas system in the South-Central Transverse Ranges

Yehuda Ben-Zion
Department of Earth Sciences
University of Southern California, Los Angeles, CA, 90089-0740
phone: (213) 740-6734; fax (213) 740-8801
e-mail: benzion@usc.edu

Start date: April 1, 2016
End date: March, 31 2018

May 2018

Abstract

The primarily goal of this project was to use the newly available denser seismic data in southern California, newly developed automatic phase picking algorithms, and updated double-difference and noise-based inversion methodologies to obtain state-of-the-art velocity models for the plate boundary region around the South-Central Transverse Ranges (SCTR). Toward this goal, we derived detailed region-scale P and S velocity models and relocated the seismicity using these models. In addition, we augmented locally the region-scale results with high-resolution information on through-going bimaterial interfaces in the San Gorgonio Pass and Cajon Pass regions, and are currently working on detection of bimaterial interfaces that connect the San Jacinto fault zone to the San Andreas Fault at Cajon pass. Specifically, the studies have focused on the following four research directions: (1) Imaging bimaterial interfaces in the sections of the San Andreas fault to the northwest and southeast from San Gorgonio Pass. (2) Double-difference earthquake tomography of the of the plate-boundary region around the South-Central Transverse Ranges. (3) Noise-based Eikonal Tomography of the plate-boundary region around the South-Central Transverse Ranges. (4) Imaging bimaterial interfaces in the northwest section of the San Jacinto fault zone and the Mojave section of the San Andreas fault. Below we provide additional details on the main results associated with each research direction. The results provide important information on structural properties of the complex plate-boundary in southern California relevant for earthquake source physics and refined estimates of seismic shaking hazard.

Main Report

(1) Bimaterial interfaces in the South San Andreas Fault with opposite velocity contrasts NW and SE from San Gorgonio Pass (*Share and Ben-Zion, 2016*)

Analysis of fault zone head waves indicates the existence of two deep large-scale bimaterial interfaces in the structure of the southern San Andreas Fault (SAF) in the South-Central Transverse Ranges with opposite sense of velocity contrast (Figure 1). One interface extends from the Cajon Pass area to the San Gorgonio Pass (SGP) region and is associated with a slower seismic velocity on the south-west side of the SAF. The second interface extends from the SGP region to the Coachella Valley and involves a slower seismic velocity on the north-east side. Tomographic imaging of alternating velocity structures supports the velocity contrast reversal across the SAF. The generation of fault zone head waves from the easternmost events with epicenters >5 km north of the SAF trace support inferences that the SAF in that area is dipping to the northeast. The observations and expected properties of bimaterial ruptures suggest that earthquakes nucleating slightly to the NW and SE of SGP tend to propagate along the SAF in the opposite along-strike directions. This is consistent with geological and seismological evidence in the Mojave and southern most sections of the SAF.

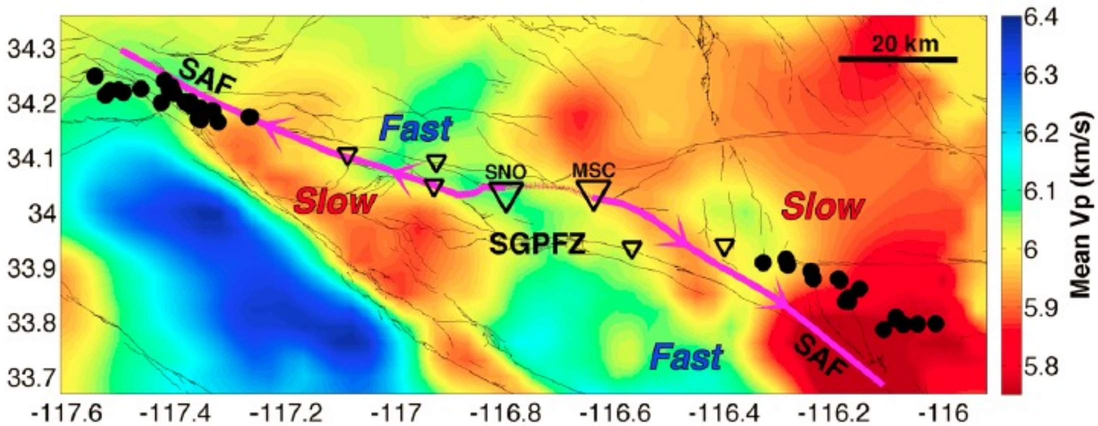

Figure 1. Events generating FZHW (black circles) recorded by stations (large triangles) SNO (NW events) and MSC (SE events). Small triangles denote stations not recording FZHW. The locations are overlain on the mean *P* wave velocities from the 3D velocity model of Fang *et al*. (2016), averaged from 3 km (top of the seismogenic zone) to 10 km (median depth of events generating FZHW). To the NW of station SNO the SW side of the SAF has slower seismic velocity, while to the SE there is a reversal in the velocity contrast across the SAF. The pink line and arrows mark, respectively, surface projections of the imaged bimaterial interfaces and preferred propagation direction of subshear ruptures. From *Share and Ben-Zion* (2016).

(2) Double-difference tomography of the San Andreas Fault system in the South Central Transverse range (*Share et al., 2017, 2018*)

We image the seismic velocity structure within and around the complex San Gorgonio Pass (SGP) "structural knot" of the San Andreas Fault (SAF) using a new double-difference tomography code incorporating both event pairs and station pairs. The event pair data help resolve fine-scale structure in seismogenic zones while station pair data allow higher resolution of structure near the surface where station density is large.

Arrival times of P and S waves generated by 18,818 M>1 local events occurring from 1/1/2010 to 30/6/2015 within a 222 km by 164 km region centered on the SGP and recorded by 262 stations are inverted for P and S velocity structures. The resulting models show low velocities at depths <7 km associated with major faults revealing complicated structure in SGP and north of that region. Large-scale low velocity anomalies extending to greater depths are also observed SE of Cajon Pass between the SAF and San Jacinto Fault (SJF) to the south, and north of the SAF near Coachella Valley. The southern edges of both low velocity regions appear to dip to the north, with the low velocity zone associated with the Coachella Valley dipping more (Figure 2). Analysis of fault zone head waves propagating along the SJF and SAF substantiate the large-scale low velocities and show they are bounded by sharp velocity contrasts. Additional features of interest are shown in various cross sections throughout the study area (Figure 3).

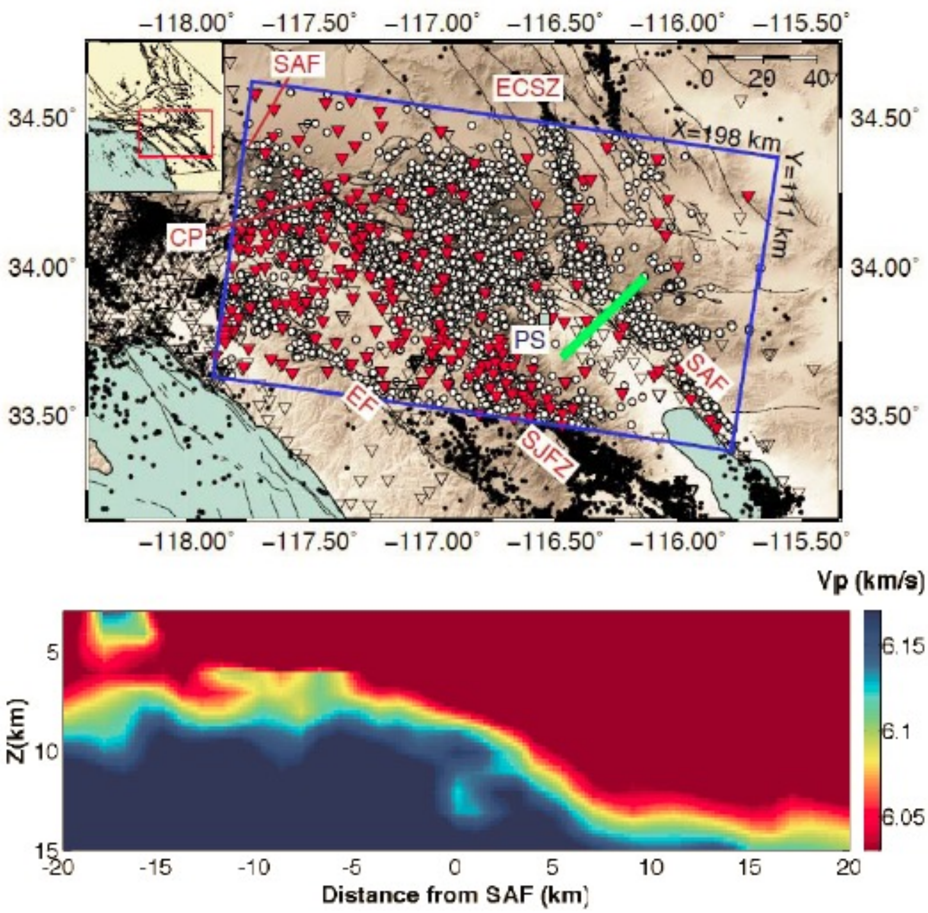

Figure 2. (top) Earthquake locations (circles) and stations (triangles) used in a double-difference tomography of the South Central Transverse Range section of the SAF. (bottom). P wave velocities along a vertical cross section following the green line in the top panel. The results show a clear lithology contrast dipping to the east across the SAF. From *Share et al.* (2017, 2018).

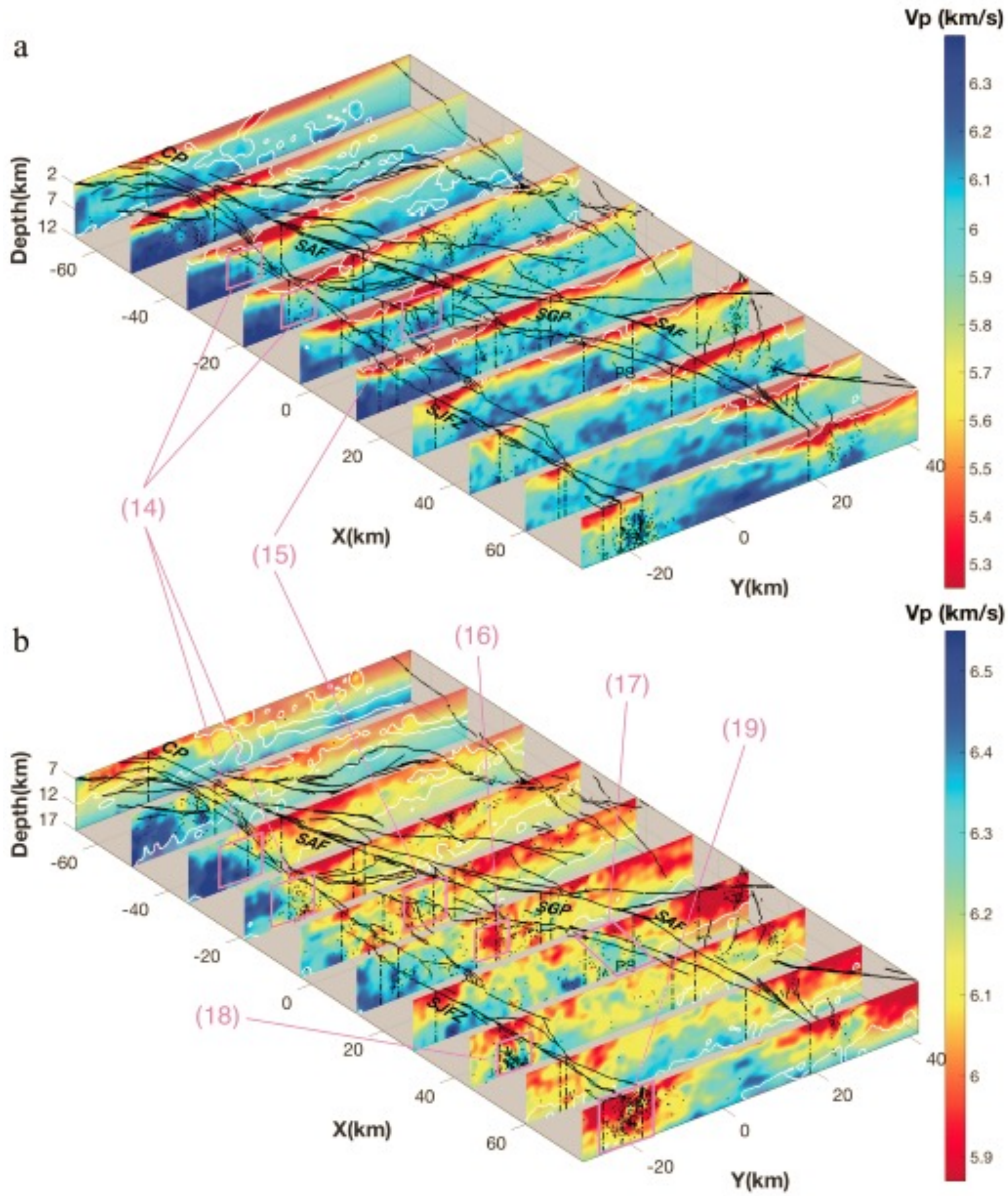

Figure 3. Inversion results for V_P at several cross-sections through the study area for depth ranges 2-12 km (a) and 7-17 km (b). Note the color bars change with depth. Small black dots denote relocated seismicity within 2 km of each respective cross-section. Black dot-dashed lines are projections in depth of major fault traces at the surface. Some prominent features are highlighted and numbered. From *Share et al.* (2017, 2018).

(3) Eikonal Tomography of the Southern California Plate Boundary Region (*Qiu et al., 2017, 2018*)

We use eikonal tomography to derive directionally-dependent phase and group velocities of surface waves sensitive to the approximate depth range 1-20 km for the plate boundary region in southern CA. Seismic noise data recorded by 346 stations in the area provide a spatial coverage with ~5-25 km typical station spacing and period range of 1-20 s. Noise cross-correlations are calculated for all 9 components data recorded in year 2014. Rayleigh and Love waves group and phase travel times are derived for each station pair using frequency-time analysis. All available phase and group travel time measurements with sufficient signal to noise ratio are used to construct travel time maps for virtual sources located at each station. By solving the eikonal equation, local propagation directions are evaluated as the normal vectors of the phase travel time contour at each location for each virtual source. The phase and group slowness are then estimated as the first order spatial derivative of the corresponding travel time along the propagation direction. Isotropic phase and group velocities, 2-psi azimuthal anisotropy and their uncertainties between 2 and 16 s period are determined statistically using measurements from different virtual sources. The obtained isotropic phase and group dispersions of Rayleigh and Love waves are then jointly inverted on a $0.05° \times 0.05°$ grid for 1D piecewise shear wave velocity structures. Larger low velocity zones are seen for the LA basin and Salton Trough. We also find 2-psi azimuthal anisotropy with fast directions parallel to geometrically-simple fault sections.

(4) Bimaterial fault interfaces along the San Andreas and San Jacinto faults in the Cajon Pass region (*Share and Ben-Zion, 2018*)

We examine waveforms generated by 7811 $M > 1.5$ events and recorded at 44 stations around Cajon Pass for the possible existence and properties of major bimaterial interfaces in the region. Analysis with automatic phase picker and visual inspection reveal clear fault zone head waves NE of the San Jacinto fault, which refract along a fault bimaterial interface from events located both near the San Jacinto basin and within the Cajon Pass region. The results imply the existence of a continuous bimaterial interface along the northern San Jacinto fault all the way to Cajon Pass that separate a slower crustal block NE of the fault from a faster block SW of the fault. The moveout between arrival times of the head waves and direct P arrivals indicate that the average velocity contrast across the bimaterial interface is about 10% in the top 10-15 km of the crust. The existence of a bimaterial interface and sense of velocity contrast suggest preferred direction of earthquake ruptures along the northern San Jacinto fault to the SE. The continuing work focuses on similar analysis of earthquake waveforms associated with the section of the San Andreas fault to the NW of Cajon Pass.

References

Fang, H., H. Zhang, H. Yao, A. Allam, D. Zigone, Y. Ben-Zion, C. Thurber and R. D. van der Hilst, 2016. A new three-dimensional joint inversion algorithm of body-wave and surface-wave data and its application to the Southern California Plate Boundary Region, *J. Geophys. Res*., 121, 3557-3569, doi:10.1002/2015JB012702.

Qiu, H., Y. Ben-Zion and F.-C. Lin. Eikonal Tomography of the Southern California Plate Boundary Region, Proceedings of workshop on Frontiers in Studies of Earthquakes and Faults, Shenzhen China, 2017, and ms. in preparation, 2018.

Share, P.-E. and Y. Ben-Zion. Bimaterial interfaces in the South San Andreas Fault with opposite velocity contrasts NW and SE from San Gorgonio Pass, Geophys. Res. Lett., 43, doi: 10.1002/2016GL070774, 2016.

Share, P.-E. and Y. Ben-Zion, Bimaterial fault interfaces along the San Andreas and San Jacinto faults in the Cajon Pass region, ms. in preparation, 2018.

Share, P.-E, H. Guo, C. H. Thurber, H. Zhang and Y. Ben-Zion, 2017. Seismic imaging of the southern California plate-boundary around the South-Central Transverse Ranges using double-difference tomography, Abstract of the Annual Meeting of the American Geophysical Union, 2017, and ms. in preparation, 2018.

Publications Supported by this grant

Qiu, H., Y. Ben-Zion and F.-C. Lin. Eikonal Tomography of the Southern California Plate Boundary Region, Proceedings of workshop on Frontiers in Studies of Earthquakes and Faults, Shenzhen China, 2017, and ms. in preparation, 2018.

Share, P.-E. and Y. Ben-Zion. Bimaterial interfaces in the South San Andreas Fault with opposite velocity contrasts NW and SE from San Gorgonio Pass, Geophys. Res. Lett., 43, doi: 10.1002/2016GL070774, 2016.

Share, P.-E. and Y. Ben-Zion, Bimaterial fault interfaces along the San Andreas and San Jacinto faults in the Cajon Pass region, ms. in preparation, 2018.

Share, P.-E, H. Guo, C. H. Thurber, H. Zhang and Y. Ben-Zion, 2017. Seismic imaging of the southern California plate-boundary around the South-Central Transverse Ranges using double-difference tomography, Abstract of the Annual Meeting of the American Geophysical Union, 2017, and ms. in preparation, 2018.